On the nature of Galactic Halo

By S.B.Pickelner and I.S.Shklovsky

1. In 1952 it was shown by one of us (1) that the sources of galactic nonthermal radioemission form a nearly spherical system concentrating toward the plane and the centre of the Galaxy. It was pointed out independently by the other author (2) that the field between the clouds should be sufficiently strong in order to retain the cosmic rays in the Galaxy. The density of the kinetic energy of the gas between the clouds could be taken as equal to that of the magnetic energy. Thus the velocity dispersion of the rarefied gas in the space between the clouds should be large and form a spherical, but not a flat subsystem. The spherical distribution of the radioemission supports this suggestion. The wide H and K absorption lines appearing in the spectra of early supergiants are also an argument in favour of the reality of fast movements of the rarefied gas. However, L.Spitzer (3) points out that at least a part of these lines belong to the stars. Spectrograms taken by G.Münch show that some of the wide lines consist of a few faint narrow lines. These phenomena may be explained by the density fluctuations of rarefied gas ($k_\nu \propto n^2$), but some other interpretations are also probable. This phenomenon supports the hypothesis that the more rarefied gas possesses a higher velocity dispersion. The existence of wide H and K lines is not the principal argument of this theory. It will be shown below that the gas of the halo is too rarefied to give observable lines.

L.Spitzer also pointed out that the existence of supersonic motions must lead to rapid energy dissipation.Consequently he considered the galactic halo to be real and its large size to be maintained by its high kinetic temperature instead of its fast motions. In this case the temperature of the gas in the space between clouds should be about one million degrees and the concentration derived from the equilibrium condition between the clouds and in the interstellar space must be $5 \cdot 10^{-4} cm^{-3}$.

2. The only reliable observational data concerned with halo are supplied by the nonthermal radioemission of the Galaxy. J.Baldwin (4) believes that there are two subsystems which could give similar spectra - the spherical halo and the "Oort-Westerhout distribution". This suggestion seems to us artificial and is a consequence of the introduction of some simplified procedures in the treatment of the observational data. Direct observations by B.Mills by means of a "cross" show a gradual increase of brightness towards the equator and a narrow maximum corresponding to the flat subsystem. The radiogalaxies NGC 5128, 4486 and 1316 also show bright nuclei and a gradual decrease of brightness in an outward direction. It may be found from an analysis of different radio data and their comparison that the density of emission near the galactic plane beyond the flat subsystem ($z \approx 1$ kps above the Sun) is about 5-10 times larger than that far from the galactic plane ($z \approx 10$ kps).

Let the differential energy-spectrum of relativistic electrons be $dN(E) = KE^{-\gamma} dE$. The emission $\mathcal{E}_\nu$ per unit volume is then proportional to $KH^{\frac{\gamma+1}{2}} \nu^{-\frac{\gamma-1}{2}}$. The average value of γ is found to be 2.6, thus $\mathcal{E}_\nu \propto KH^{1.8}$. The slow decrease of $\mathcal{E}_\nu$ upwards is the consequence of a slow decrease of K and H. As the electrons move along the magnetic lines we can assume K to be proportional to H. The error involved in this assumption is insignificant. Thus $\mathcal{E}_y \propto H^{2.8} \propto K^{2.8}$. Introducing the ratio of the value found for $\mathcal{E}_y$ above at $Z \approx 1$ and 10 kps, we obtain the value of H (and consequently K) in these two corresponding points to be different by a factor of about 2. As the motion of protons and other cosmic ray particles are similar to that of electrons, their energy density in the upper layer is also about twice smaller than that near the galactic plane and is approximately equal to 0.5 eV/cm^3. The pressure of cosmic rays constitutes a third of its energy density. It is known that cosmic rays may be retained in the Galaxy by the magnetic field, if the magnetic pressure is larger than the cosmic ray pressure. Consequently, the lower limit of the field strength is about $H_{10} \approx 3.10^{-6}$ and $H_1 \approx 6.10^{-6}$. Possible error involved here is not very large. If the emission of the flat subsystem were also of a nonthermal character, as it is suggested by B.Mills, it might be explained by that the field in spiral arms is a little stronger than outside these arms.

3. The magnetic and cosmic ray pressure at $Z \approx 10$ kps must be balanced by the weight of the gas above this level. Thus

$$\int_{10}^{\infty} g\rho\, dz = \frac{H_{10}^2}{8\pi} + p_{Kr} + \frac{1}{2}\rho v_z^2 + p_g \approx 3\frac{H_{10}^2}{8\pi}$$

*) See page 9.

The scale of height may be taken as 5 kps. We deduce then n_{10} about $0.6 . 10^{-2} cm^{-3}$, which is ten times larger than Spitzer's value. The Spitzer's halo cannot be retained in our Galaxy. If the density is large the temperature cannot be very high, otherwise the clouds would not be in equilibrium. High temperature is not necessary now since the halo may be supported by the magnetic and cosmic-ray pressures. The magnetic field can hardly be regular, since the poloidal field does not keep the cosmic rays, while the toroidal field prevents the cosmic rays from spreading in the Galaxy and reveals some other difficulties (large value of the magnetic flux and so on). If the field is not regular it cannot be a static one. The magnetic forces will lead to a motion of the matter and the dynamic equilibrium must be established, when the densities of the magnetic and the kinetic energies are about the same. In this case the mean velocity of macroscopic motions is about 100 km/sec. The gravitational equilibrium for the layer between Z = 1 kps and 10 kps gives an average value n about $10^{-2} cm^{-3}$.

4. The principal objection aqainst high velocity mass motion is the strong energy dissipation in shock waves. However the presence of the magnetic field and the cosmic rays increases the sound velocity. If the magnetic and kinetic energies are the same, the sound velocity in the direction normal to H is equal, or greater, than the gas velocity. The shock wave is weak in this case and the dissipation is not so large. An solution for the weak perpendicular magneto-hydrodynamic shock waves was obtained. Accor-

ding to F.Hoffmann and E.Teller (5) the increase of enthropy in that wave is

$$\Delta S = -\frac{(\Delta x)^3}{12 T_1}\left(\frac{\partial^2 p^*}{\partial x^2}\right)$$

where $x = \rho^{-1}$, $p^* = p + \frac{1}{8\pi\rho} H^2$

If $p_1 << \frac{1}{8\pi} H^2$, the equation may be reduced to the form

$$\frac{\Delta Q}{2\frac{H^2}{8\pi\rho}} = \frac{1}{4}\left(\frac{\Delta x}{x_1}\right)^3$$

The left side is the ratio of irreversible heating per unit mass to the total amount of kinetic and magnetic energies per unit mass as a result of a passage of a single wave. The radiative cooling increases the irreversible dissipation. But this effect is not very pronounced, if $T_1 < 25000^\circ$. Besides, the reversible transformation of the kinetic into the magnetic energy retards the individual wave, without decreasing the total average amount of the kinetic energy. The relative compression $\frac{\Delta x}{x_1}$ was calculated by means of general equations of the perpendicular magneto-hydrodynamic waves. If the condition $\frac{1}{2}\rho v^2 = \frac{1}{8\pi} H_1^2$ is fulfilled $\frac{\Delta x}{x_1} = 0.54$. Consequently, only about 4 per cent of energy is dissipated in a single wave. If the density of the magnetic energy is greater than that of the kinetic one (for instance, if the differential rotation stresses the magnetic lines) the relative dissipation decreases as H_1^{-4}. A calculation of the dissipation, taking into account the pressure and energy densities of the cosmic rays, had been done. The same value was obtained.

Let the characteristic dimensions of the motions in the halo be $\ell \sim 100$ ps. The characteristic time t_1 will then be about 10^6 years. The time of dissipation in the chaotic magnetic field $t_0 \sim 25\ t_1$, while in the absence of the field, it will be about t_1. The diminution of the dissipation in the magnetic field may be important not only for the problem of interstellar gas, but also for that of turbulent motion in stellar atmospheres.

To maintain the motions in the halo a powerful source of energy is required. The power of this source must be about

$$\frac{1}{t_0}\int\left(\frac{1}{8\pi}H^2 + \frac{1}{2}\rho v^2\right) d\Omega \approx 3.10^{41}\,\mathrm{erg/sec.}$$

All known mechanisms - novae and supernovae explosions, the radiation pressure of hot stars, the expansion of H II regions and the "rocket effect" are insufficient.

The Dutch scientists showed (6) that the neutral hydrogen in the nucleus of the Galaxy ($n_0 \approx 0.4\ \mathrm{cm}^{-3}$) has the radial velocity dispersion of about 50 km/sec. If the magnetic energy is equal to the kinetic energy and K is proportional to H then the radioemission of the nucleus must be about 100 times greater, than the halo of radioemission. This is in accordance with observations and may serve as a proof of the correctness of some of the above suggestions. The magneto-hydrodynamic waves must be propagating outward from the nucleus of the Galaxy. The energy flow $\frac{1}{2}\rho v^3 S$ is about 5.10^{41} erg/sec, namely just sufficient to compensate dissipation. The magnetic field of the waves in the vicinity of the nucleus is larger than the mean field in the halo. It explains the large extension of the region where the nonthermal radioemission is relatively strong. This region is considerably larger, than the 21 cm region. The increase of nonthermal radioemission towards the nucleus, same as that of the density of the magnetic and the kinetic energies is also an argument in favour of the hypothesis that the nucleus is the principal factor, explaining the motions in the halo. The mechanism supporting the motions in the nucleus is unknown yet, but the motions are observed.

5. The value of ΔQ permits us to compute the increase of gas temperature when a single wave is passing. For the average conditions $\Delta T_i \approx 30000^\circ$. It was calculated that a wave ionises one per cent of the hydrogen. After the time interval t_1 the temperature falls to within $10000^\circ - 15000^\circ$. Every subsequent wave will ionise about one per cent of gas. After this, the temperature will again fall to $\approx 10000^\circ$. This quantity depends but very little from the initial conditions, because at low temperatures the process of cooling is very slow. The stationary degree of ionisation may be from 10 to 80 per cent. It is a function of gas density, of t_1 and other physical conditions. The ionisation would be complete, if the magnetic field were absent. The determination of the ionisation from observations permits us to define more precisely the rate of dissipation.

6. The theoretical computation is based upon simple models and may be lacking accuracy. It is necessary to con-

firm the principal results by means of direct observations. Examples must be given to show the existence of halo and other gaseous systems with a high velocity dispersion, but with low temperature and ionisation. The Australian scientists (7) received 21 cm isophots for the Magellanic Clouds. These isophots cover the region which is much larger than the region of optical emission. The radial velocity dispersion is about 50 km/sec. The computed concentration of the neutral hydrogen on the periphery of the LMC is about $0.8 \cdot 10^{-2}$ cm^{-3}. LMC has traces of spiral structure. It is probable that LMC has a halo similar to our Galaxy. The nucleus of our Galaxy also contains partly neutral gas with high velocity dispersion. Observations in the 21 cm region in the Coma cluster (8) are especially interesting. The mass of neutral hydrogen is about 10^{14} M , which is nearly equal to the total mass of the cluster from the virial theorem. The great mass, the large extension and some other reasons lead to a supposition that we have here to do with intergalactic gas. The dispersion of the radial velocity of this gas is about 500 km/sec. If the magnetic field would be absent this intergalactic gas would be completely ionised. The field may decrease the dissipation in the shock wave, if the energy of the field is not less than the kinetic energy. Consequently, the examples given above ~~p~~represent an argument in favour of the equipartition of the magnetic and the kinetic energy.

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* The Coefficient 3 is too large, but we retain it since according to modern data the density of the energy of cosmic rays exceeds 1 eV/cm^3, because the energy spectrum of the cosmical particles was prolonged towards the region of small energies.